The Impact Of Gravity Waves, Cloud Nucleation Threshold and Convection on Stratospheric Water and Tropical Upper Troposphere Cloud Fraction

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Some of this material can be found in: Schoeberl, M., et al., 2016, Earth and Space Science, 3, doi: 10.1002/2016EA000180.

Overall UT/LS H_2O Science Questions

- What controls tropical UT/LS water vapor and upper tropospheric clouds? This is important since increases in stratospheric water vapor and clouds can alter the surface radiative forcing and increase polar ozone loss [Solomon et al. 2010; Zhou et al. 2014, Keith et al., 1999].

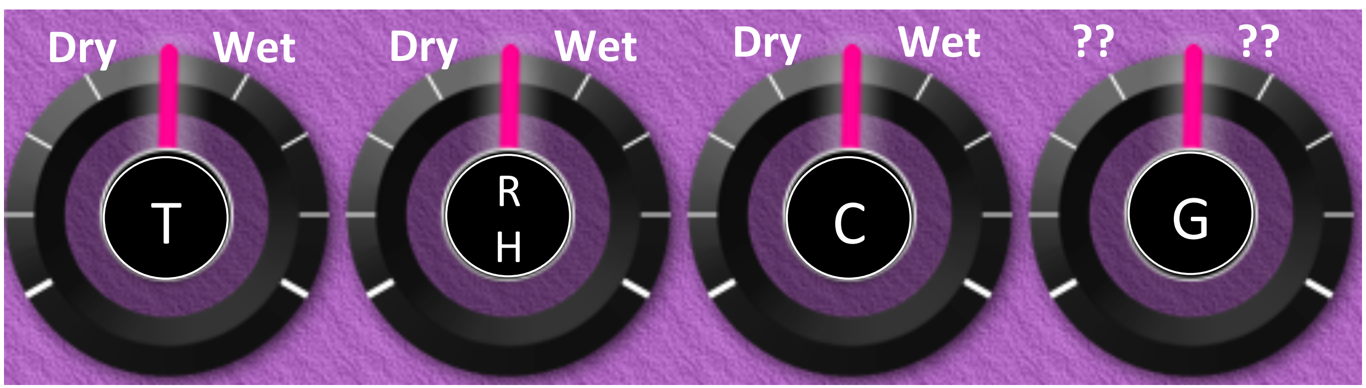
- Can we accurately simulate the tropical tropopause dehydration process and cloud formation in the tropical tropopause layer (TTL) and figure out the key parameters that control these process?

What We Have Learned So Far

UTLS water vapor is controlled by at least **four** knobs.

- Tropopause temperature – warmer T means more strat. water
- Nucleation threshold RH for clouds – higher RH means more strat. water.
- Convection – more/higher convection more strat. water
- Gravity waves - Suppresses temperatures [Kim and Alexander, 2015] and increase cloudiness [Ueyama et al., 2015].

Controls on Tropical LS Stratospheric Water



Tropopause Temperature

Nucleation RH Threshold

Convective Processing

Gravity Waves

But what is the actual sensitivity of the system to these parameters?

Approach

Use our forward domain filling (FDF) Lagrangian model of the upper troposphere and lower stratosphere performing 8 year experiments.

- Use MERRA & MERRA-2 winds, temperatures and diabatic heating
- Fully coupled cirrus model
- Add mid-frequency gravity waves – waves not resolved in the 6 hr reanalysis fields
- Use convection from MERRA or Pfister satellite product
- Use observations of stratospheric water from MLS and UTLS cloud fraction from CALIOP to baseline model results.

Other publications:

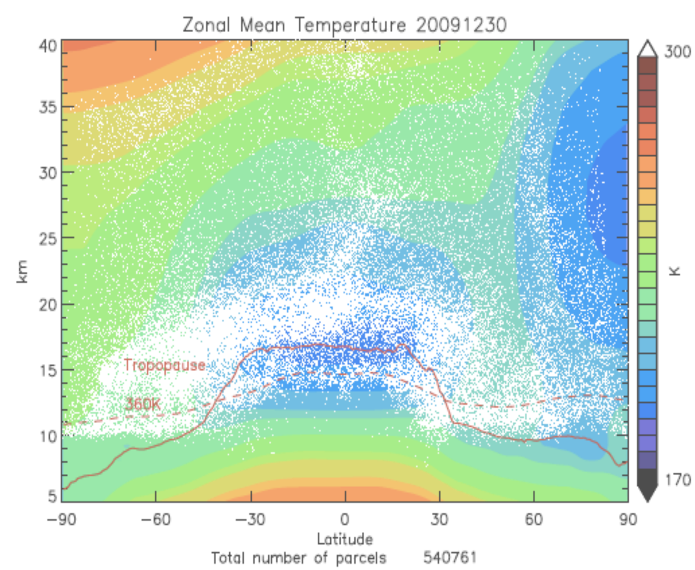
Schoeberl and Dessler (2011) ACP

Schoeberl et al. (2014) ESS

Wang et al. [2015] ACP

Schoeberl et al. (2015) ESS

Schoeberl et al. (2016) ESS

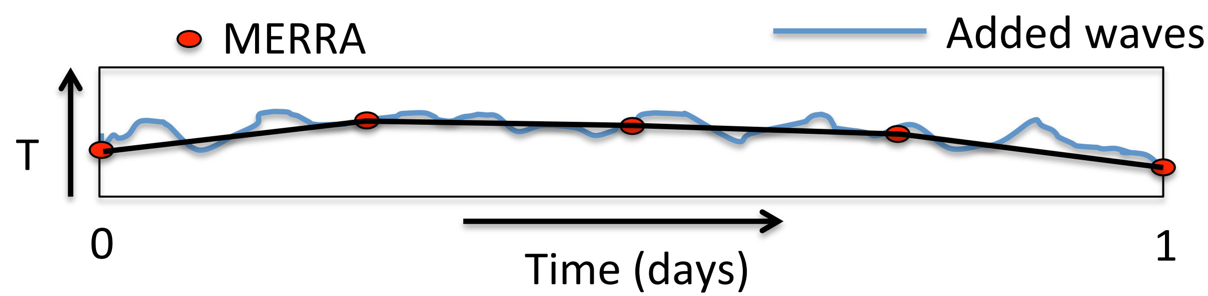


Specific Model Parameters

- MERRA with -0.5K temperature offset (based on GPS RO)
- MERRA-2 with no temperature offset
- Variable mid-frequency gravity wave spectrum

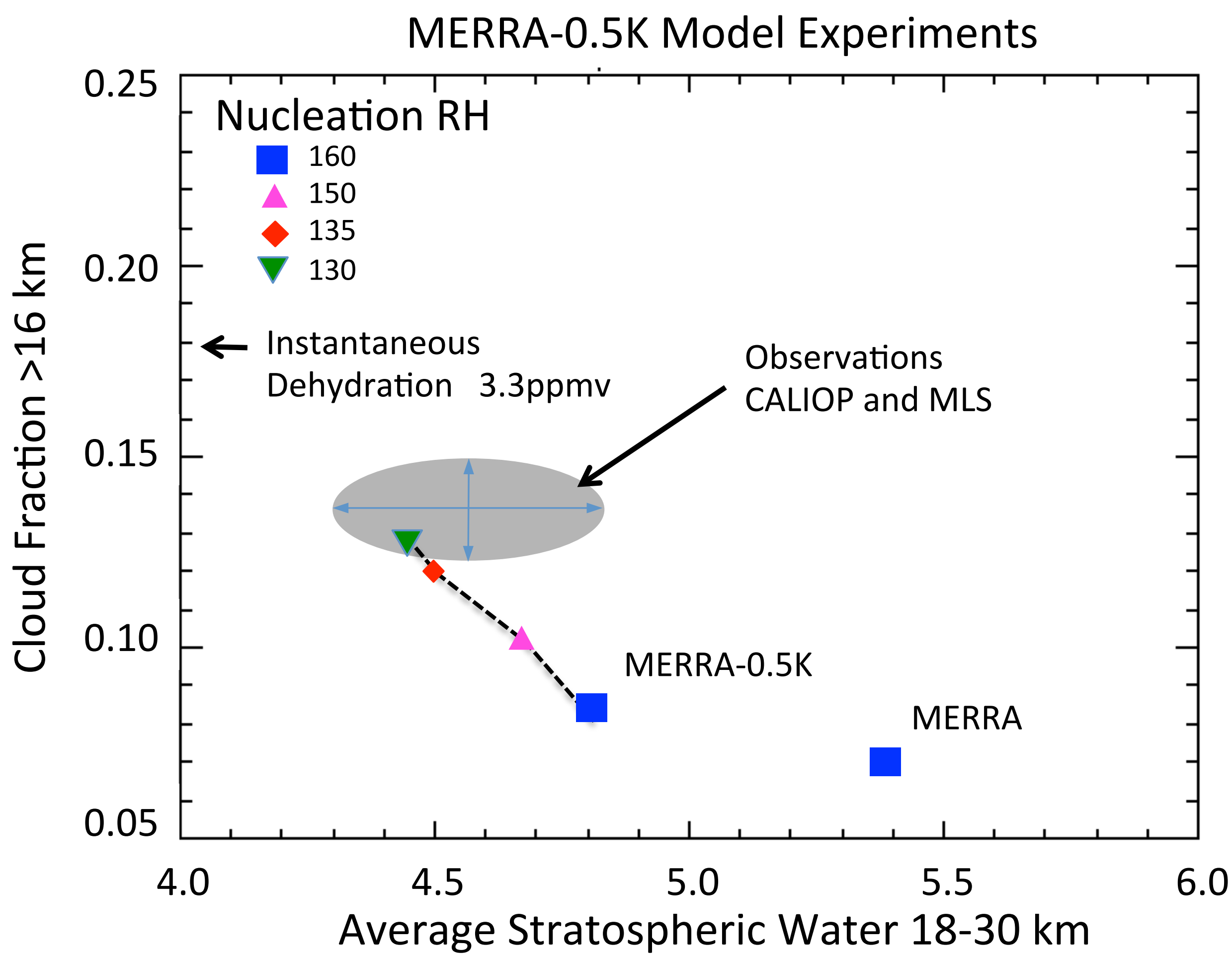
$T' = T_0(\omega)^{-1}$

$\omega > 1\ \mathrm{day}^{-1}$



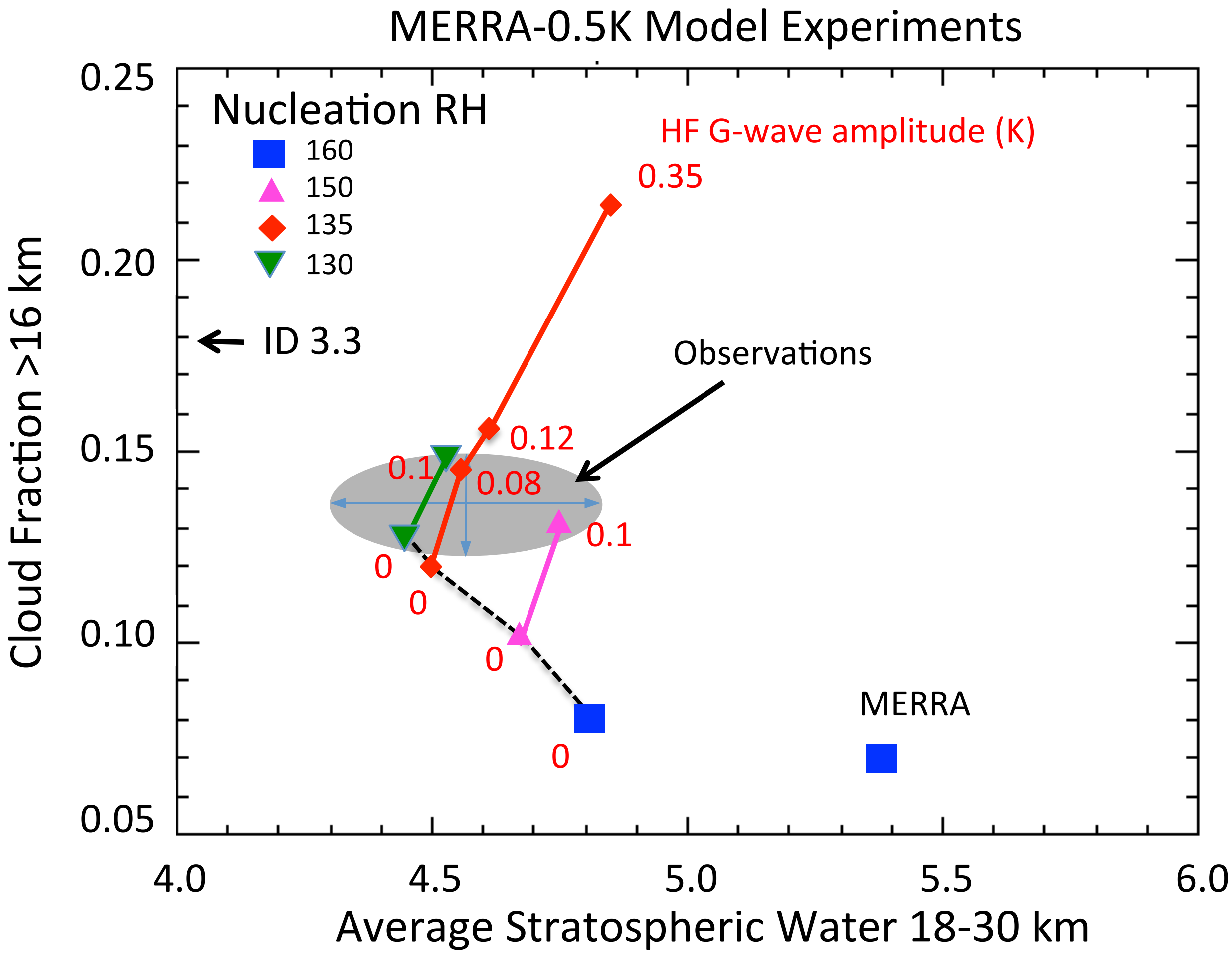
- Convective (anvil) ice from MERRA and satellite based convection from Pfister.

Role of the Nucleation Threshold RH



Decreasing the temperature decreases water and increases clouds
Decreasing the nucleation RH decreases water and increases clouds

Role of Gravity Waves



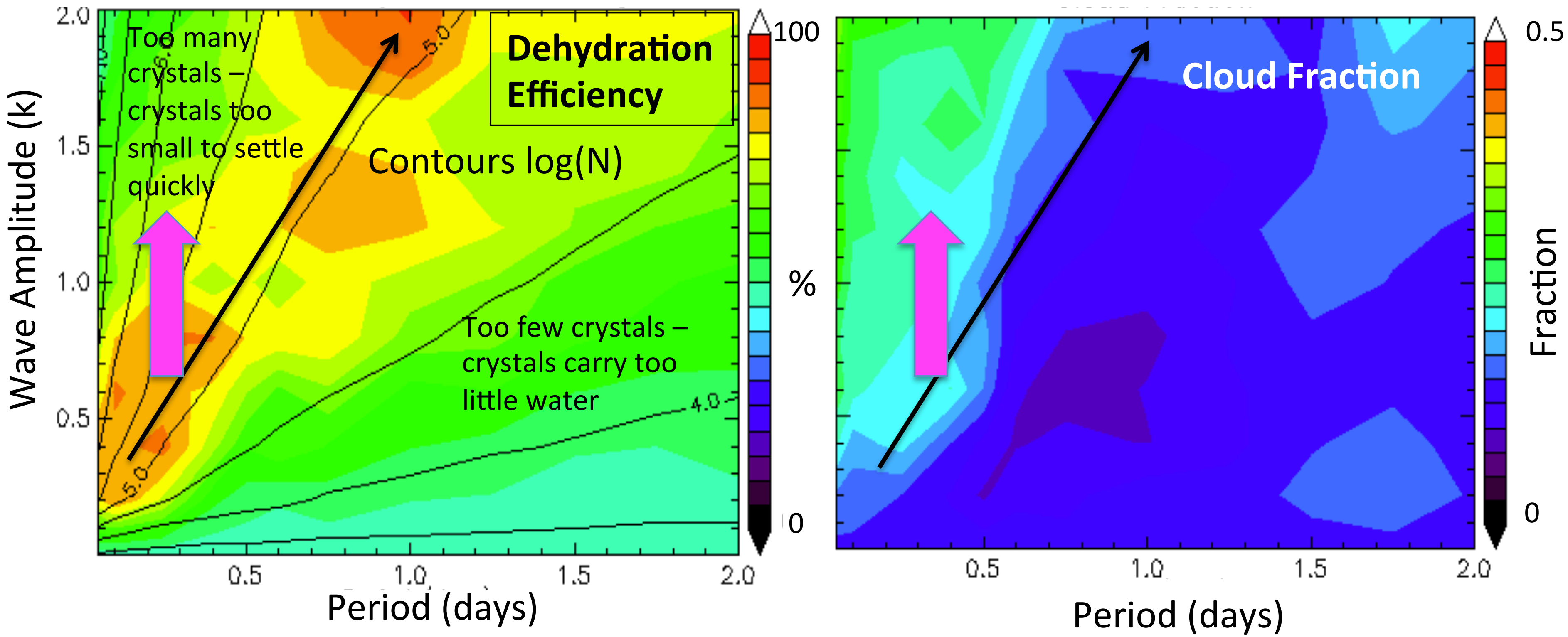
Decreasing the Temperature decreases water and increases clouds

Decreasing the Nucleation RH decreases water and increases clouds

Increasing the gravity wave amplitudes increases both clouds and water (slightly)

<u>This result is somewhat counter intuitive.</u>

Overall Dehydration Efficiency of Monochromatic Gravity Waves



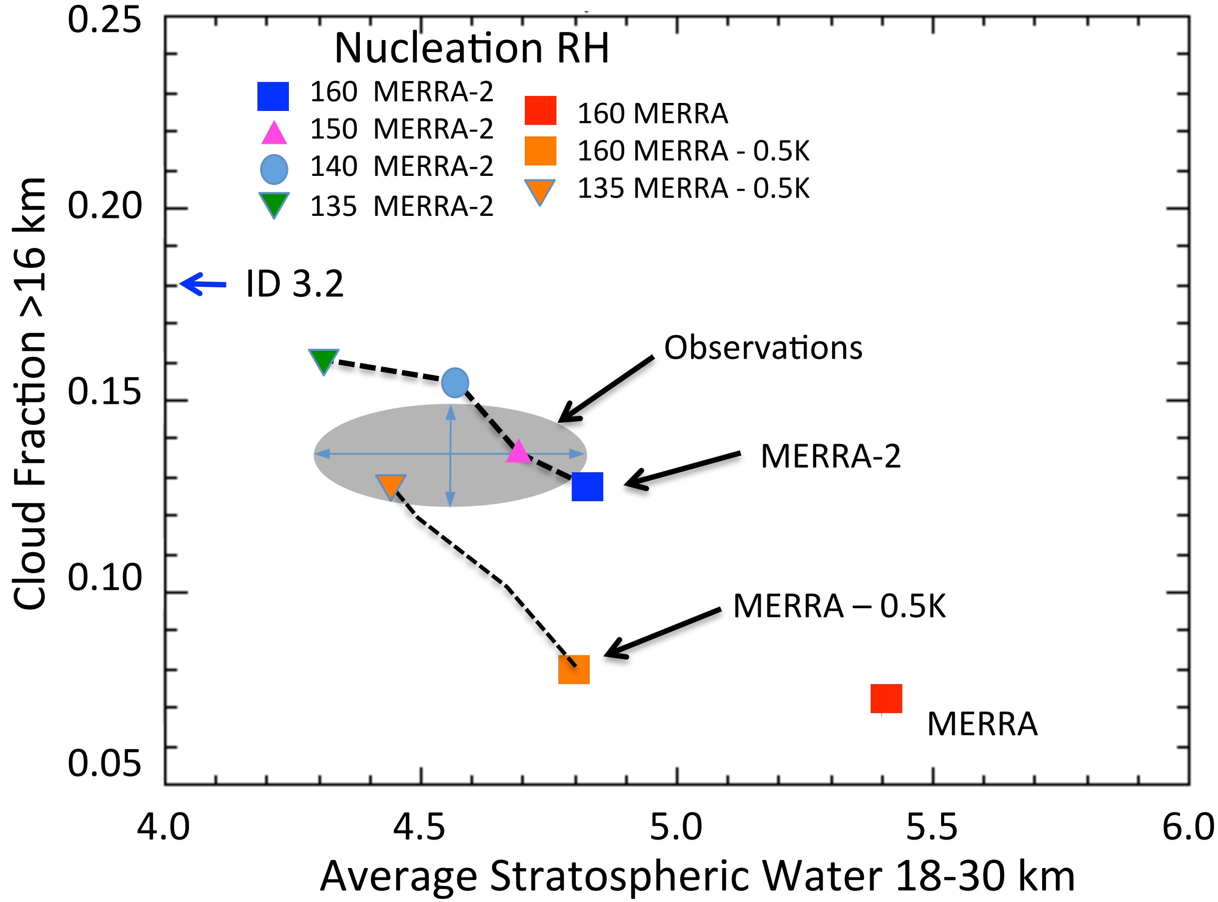
Max dehydration efficiency for monochromatic waves occurs roughly along a line that line corresponds to the nucleation of N~ 3.010^5 m^{-3} or ~3000 L^{-1} ice crystals. Higher amplitude gravity waves generate more ice crystals and reduce the dehydration efficiency.

Schoeberl, M. R., E. J. Jensen, and S. Woods (2015), Gravity waves amplify upper tropospheric dehydration by clouds, Earth and Space Science, 2, doi:10.1002/2015EA000127

MERRA-0.5K vs. MERRA-2

No Gravity Waves!

MERRA-2 Model Experiments

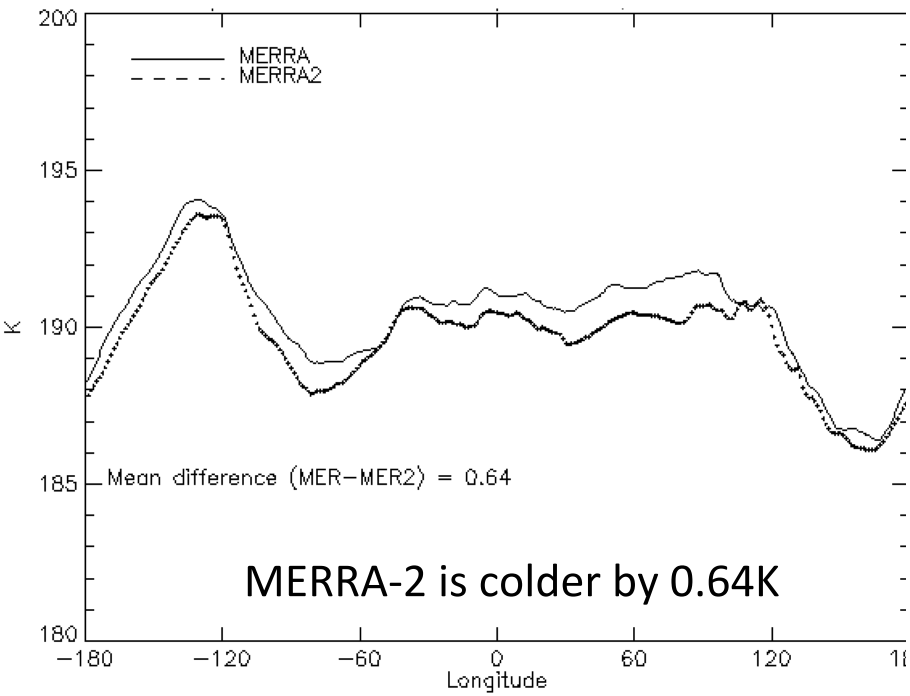


MERRA-2 without gravity waves does better than MERRA-0.5K

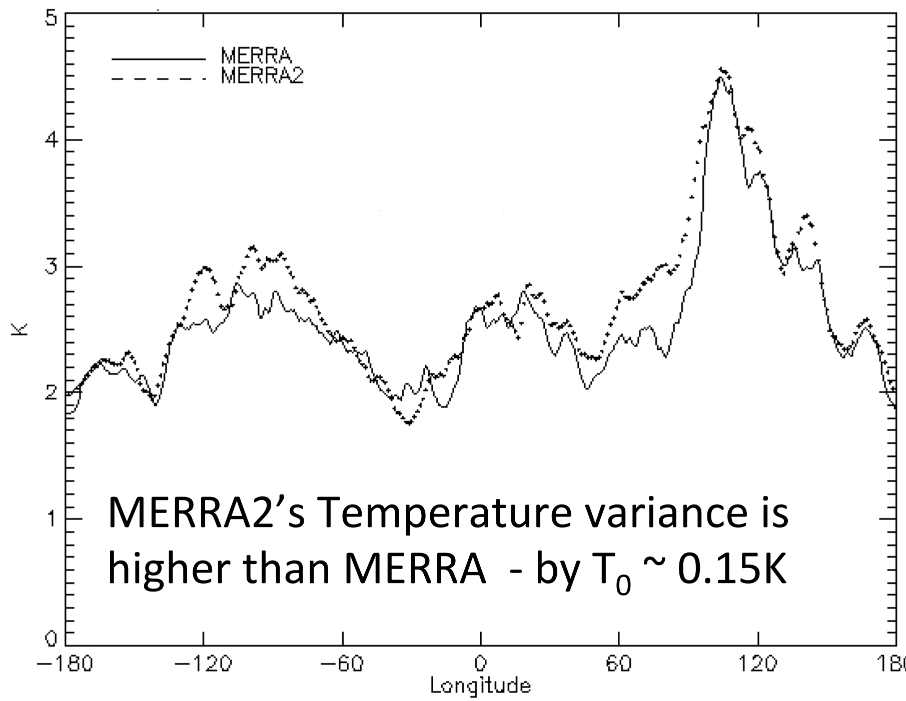
So WTF?

- MERRA gets good agreement but requires colder tropopause and gravity waves.
- MERRA-2 needs none of that. Why?

Equatorial 85 hPa T, DJF 2008-9



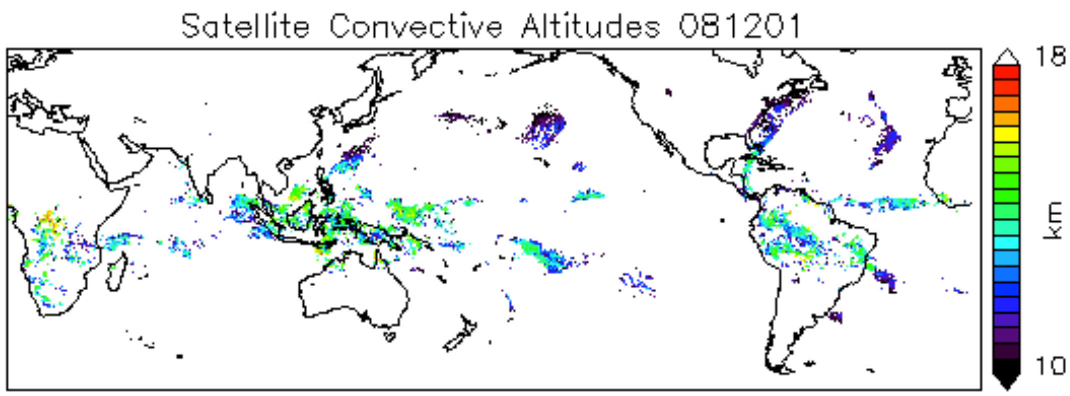
Equatorial 85 hPa STDev, DJF 2008-9

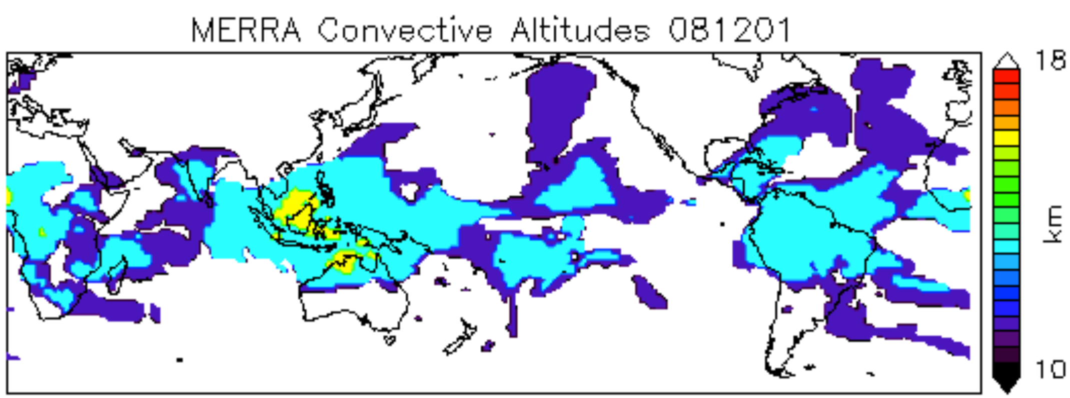


MERRA-2 assimilation of GPS-RO corrects the MERRA tropopause warm bias.
The higher variance in MERRA-2 is compensating for gravity waves we needed in MERRA

Convection

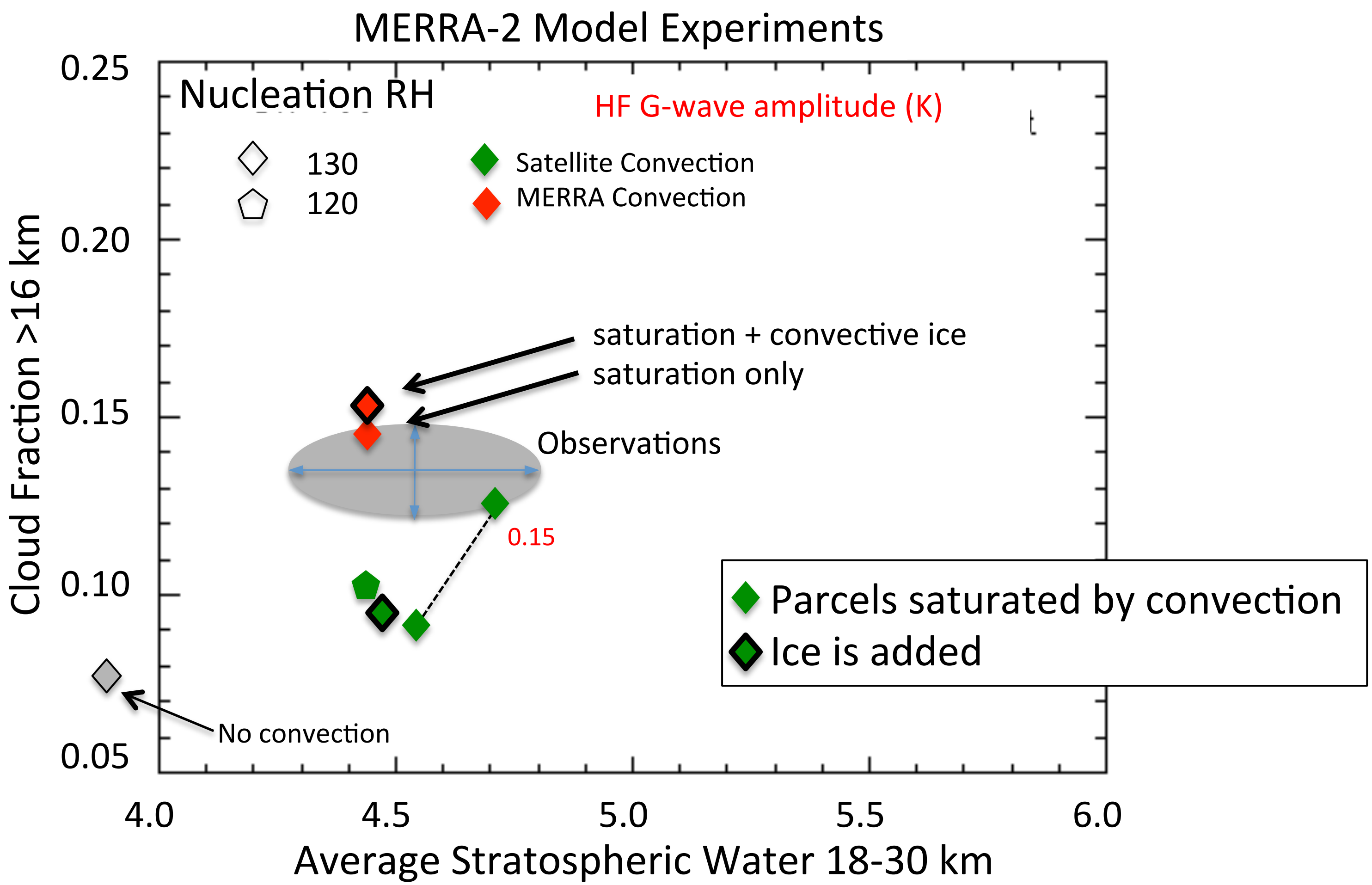
- Convective processes are a key component of the UT water vapor budget
- MERRA convection is the anvil ice product
- MERRA-2 does not separate anvil ice from cloud so we use MERRA convection with MERRA-2 winds. Convective schemes (RAS) are the same in both reanalyses.
- <u>Satellite convection</u> is generated by L. Pfister using a combination of GPM, CALIOP and IR data. The resolution of this data is much finer than MERRA convection.





General agreement, but MERRA convective field cover a wider area.

Role of Convection



Decreasing the Temperature decreases water and increases clouds
Decreasing the Nucleation RH decreases water and increases clouds
Increasing the gravity wave amplitudes increases both clouds and water (slightly)
Convection increases water and clouds but adding ice does not.

Conclusions

- Control of Stratospheric Water Vapor
  - Tropopause temperature and nucleation threshold exert the strongest control on stratospheric water.
    - Lower nucleation thresholds and lower temperatures both decrease water
  - MERRA-2 is better than MERRA as far as tropopause temperatures
    - MERRA - 2 assimilates GPS RO
  - Global TTL Nucleation threshold is ~130-140% best fits the observations
    - Combination of heterogeneous and homogeneous nucleation?
- TTL Cloud Fields
  - Cloud amount increases with lower temperatures and/or lower nucleation RH thresholds – not surprising
  - Cloud amount increases with increasing gravity wave amplitudes
    - But that doesn't affect strat water much – slight increase in H_2O with GW amplitude
  - MERRA-2's colder tropopause and higher T variance reduces the requirement for gravity waves needed by MERRA simulations.
- Convection
  - Significant differences in cloud fraction between <u>satellite convection</u> and <u>MERRA convection</u> – likely due to resolution
  - Convective parcel saturation adds ~0.7 ppmv H_2O to the overworld stratosphere (<18%) – adding ice has no effect.
  - Added stratospheric water about the same for both convection types

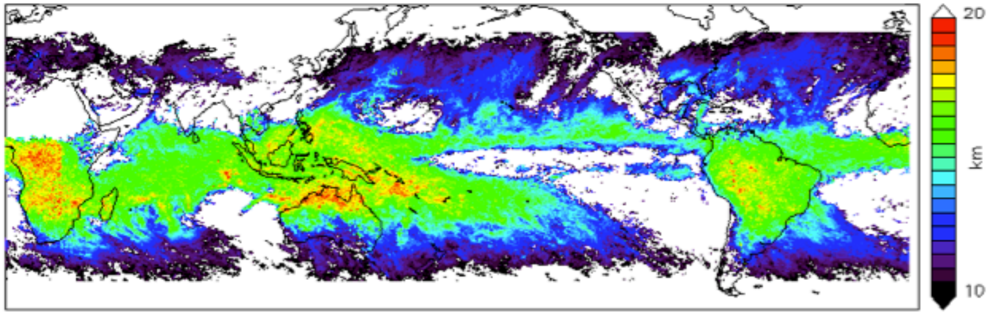
Acknowledgements

- ATTREX Project
- The CALIOP and MLS science teams
- NASA Grant NNX13AK25G

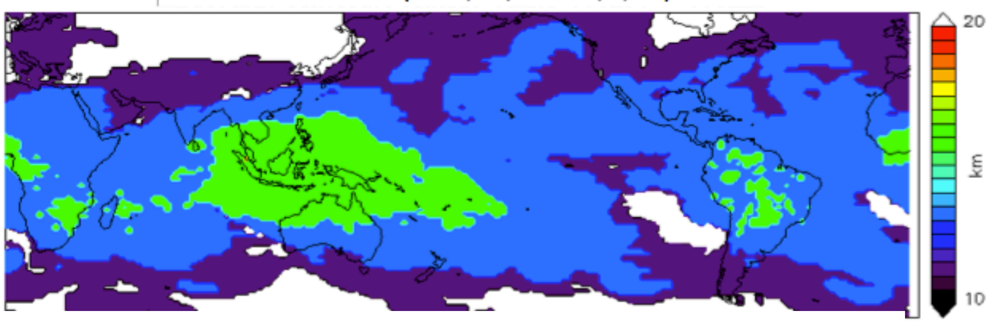
Additional Slides

More Comparisons between MERRA Convection and Satellite Convection

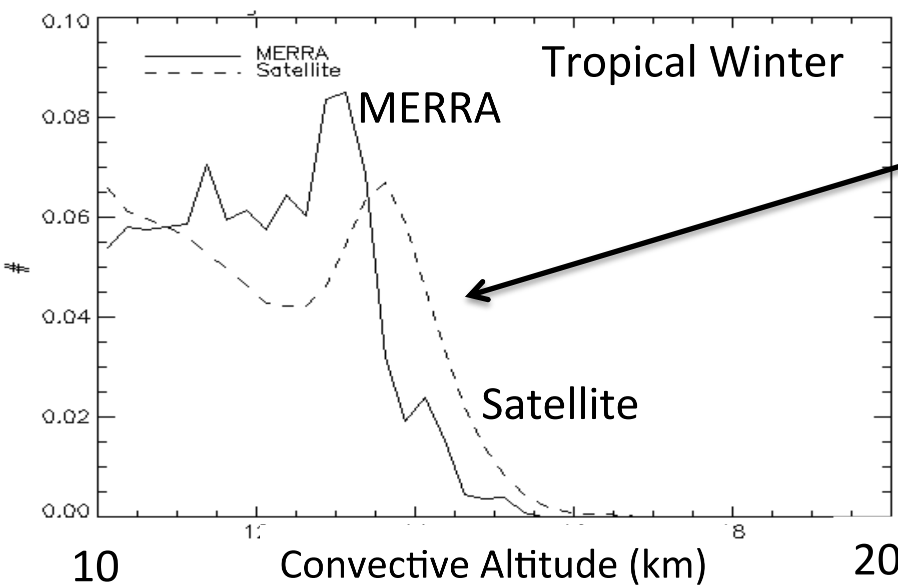
Maximum Altitudes (2008/12/1-2009/2/28) – Satellite Based Convection



Maximum Altitudes (2008/12/1-2009/2/28) – MERRA

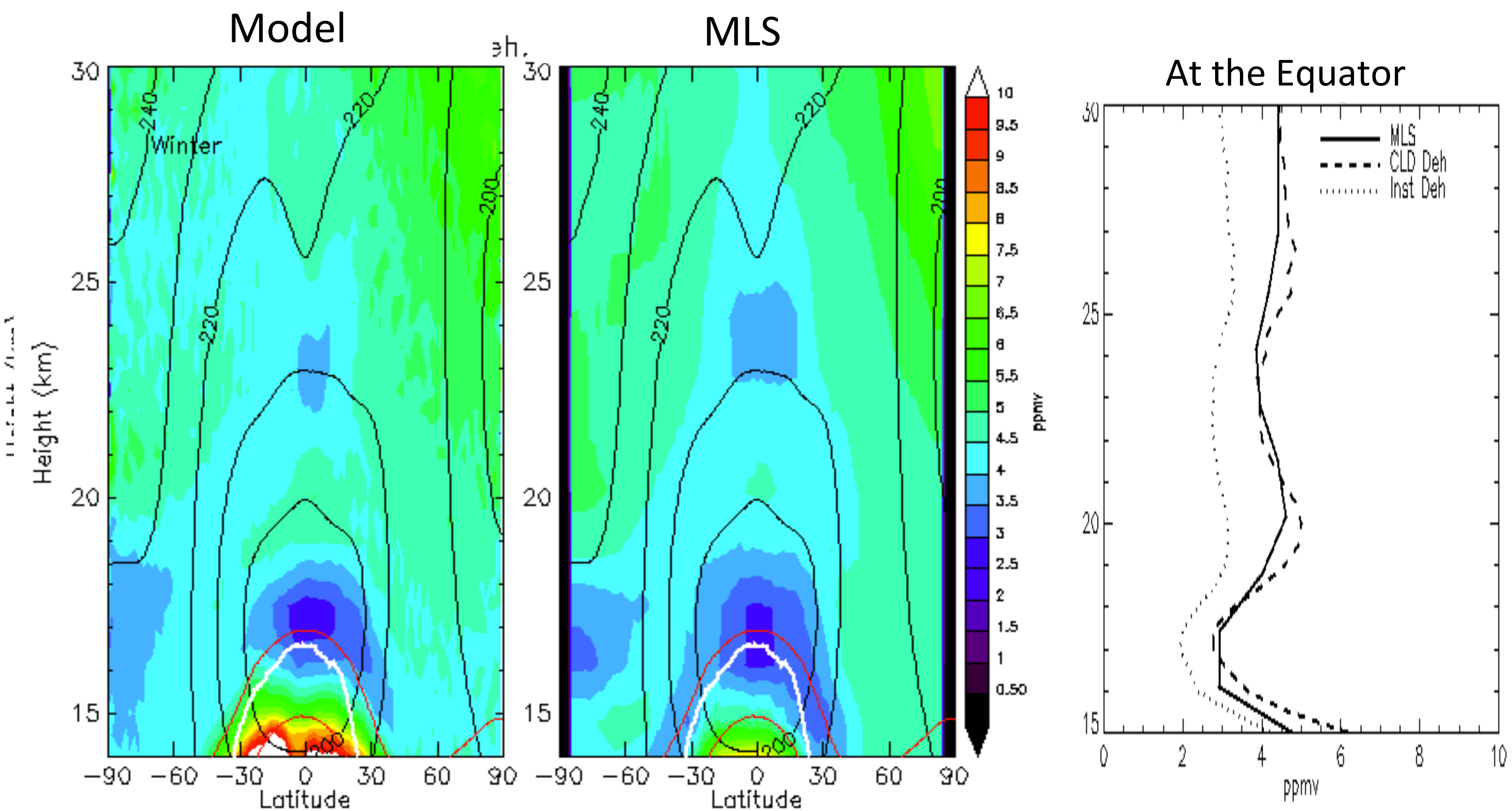


Average Convective Altitudes (2008/12/1-2009/2/28)



Satellite convection is systematically higher than RAS (MERRA) convection. But these are not a large number of events.

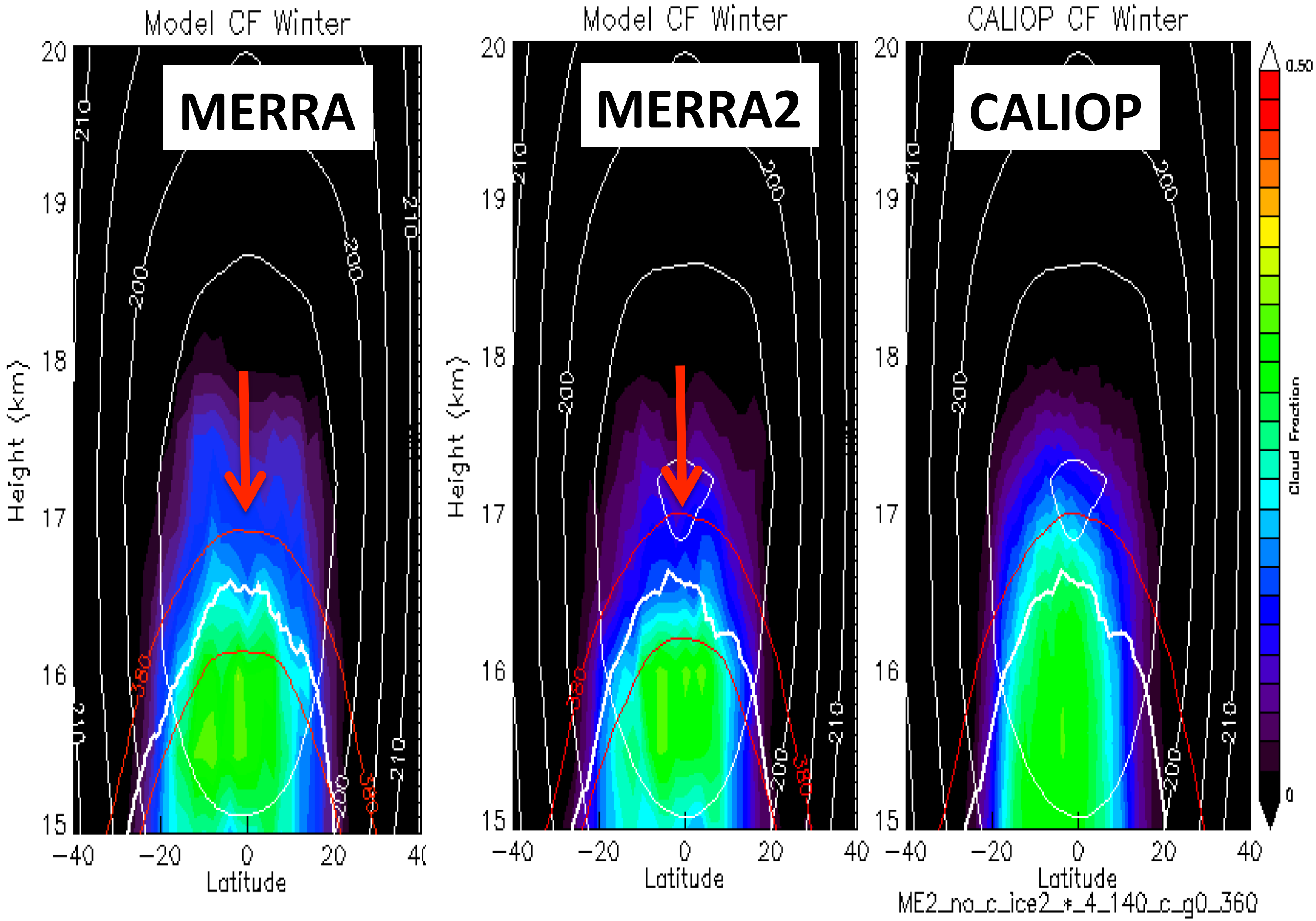
Water Vapor



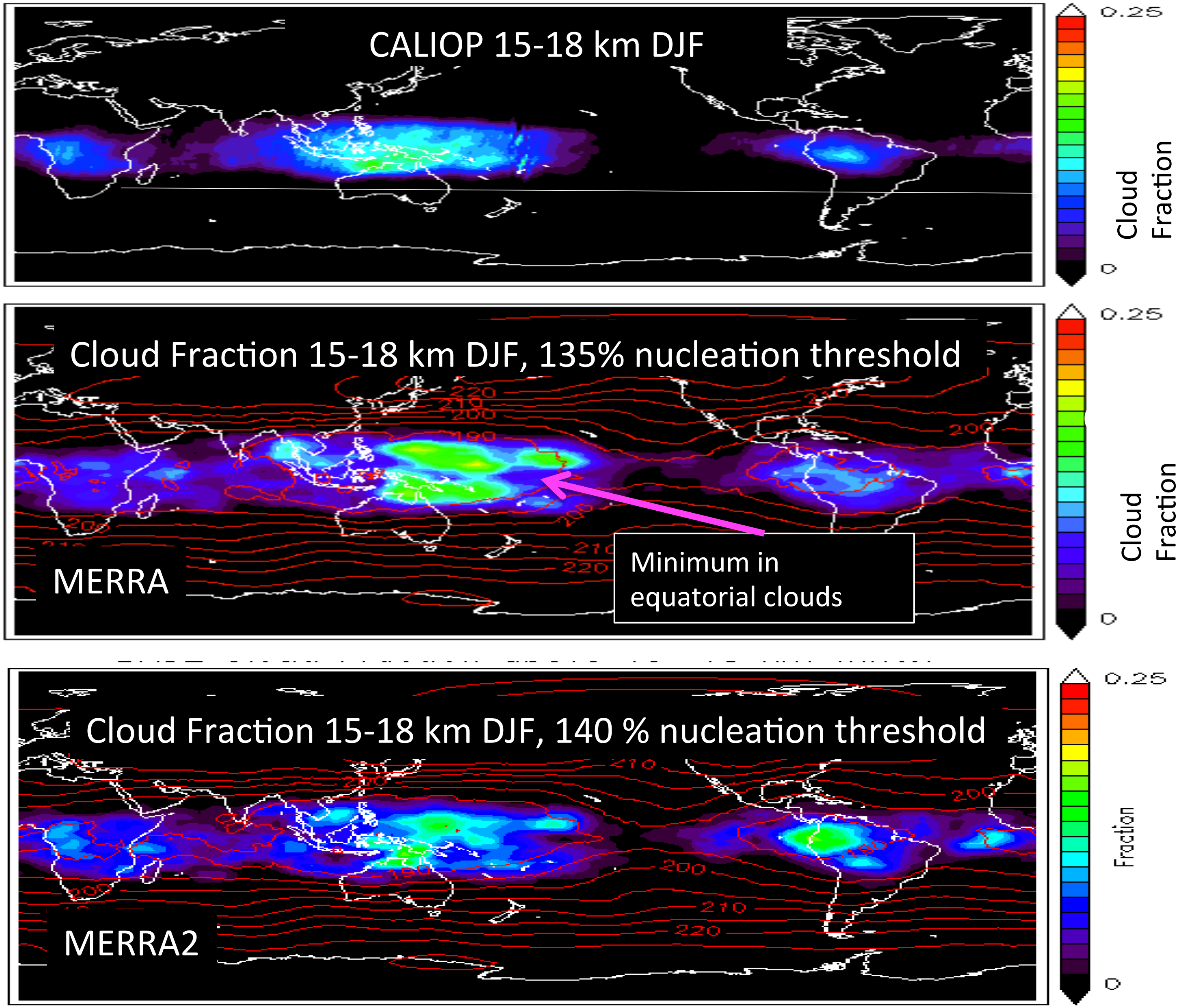
Model
MLS
At the Equator
Winter
240
220
200
Height (km)
Latitude
ppmv
MLS
CLD Deh
Inst Deh

Zonal Mean Cloud Frequency ± 40^0

Winter 2008/9

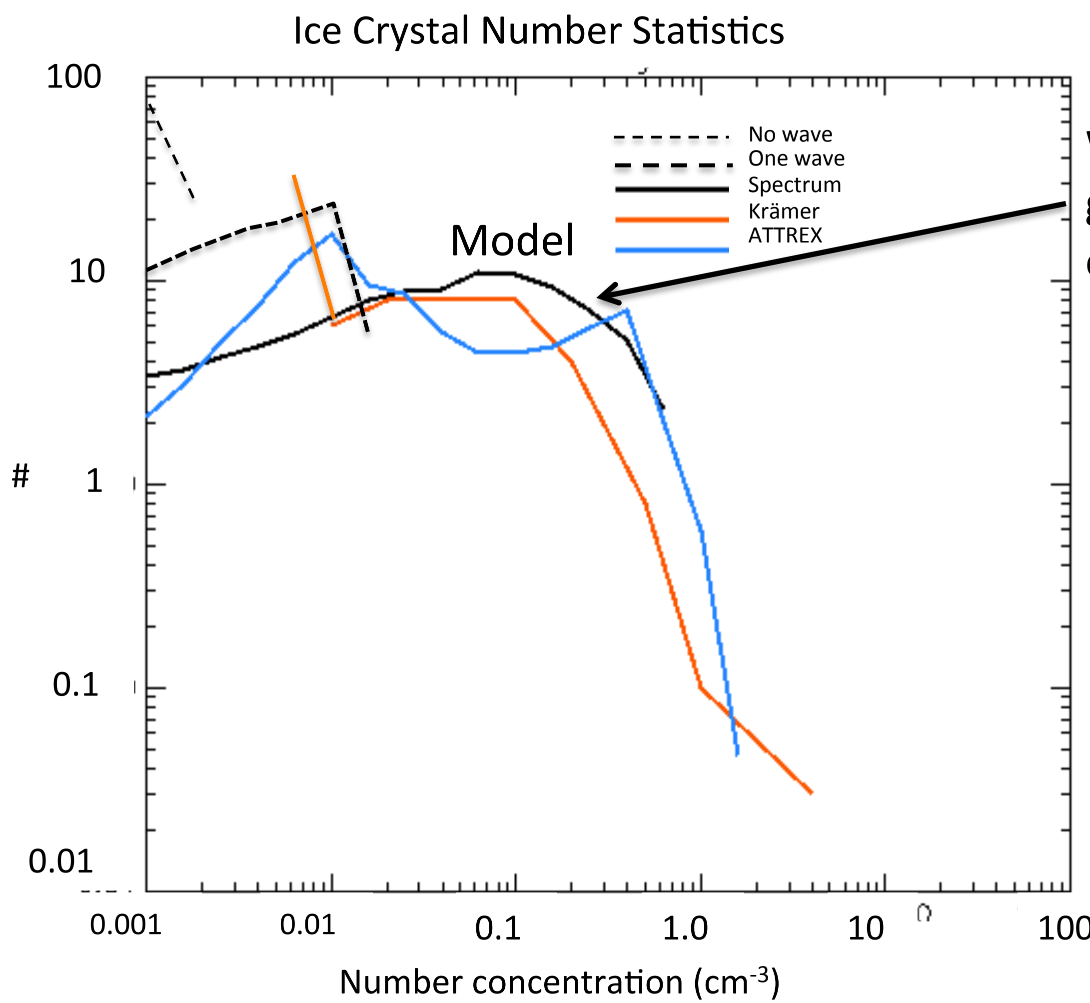


Cloud Fields – Winter 2007/8



Comparison to Observations

We use a wave spectrum from Jensen and Pfsiter [2004]



With a wave spectrum we get a reasonable distribution of ice particles.

Net dehydration efficiency ~120-130% RH even though the nucleation threshold is 160%